Application of the dynamic characteristics of shape-memory polymers to climate adaptive building facades

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Abstract

This project addresses the challenges of designing adaptive façade systems with 'dynamic' or 'smart' materials. Presented are a series of self-shading building tiles that apply the attributes of a class of polymers with shape memory characteristics. The smart material, adaptive, and reconfigurable tiles (SMART Tiles) are designed to wrinkle and reposition themselves in response to incoming solar radiation to shade building surfaces and lower thermal transmission. The workflow and design process of constructing physical models are discussed, including casting, shape programming, and tile prototyping. Stepping into the emergent field of building self-regulation with programmable matter, this project is part of the shift towards a built environment that adapts to subtle environmental fluctuations of temperature, light, humidity, and pressure via material properties. Equally important to the team is that the dynamic aspects of the SMART Tiles appeal to the imagination and viscerally (re)connect a building occupant to the environment.

Key words: dynamic materials, shape memory, adaptive façade, biomimicry

1. Introduction

Henri Bergson's ideas on matter, which includes "modifications, perturbations, changes in tension or energy – and nothing else," [1] position us between abstraction and experience, and have served as a conceptual guide for this work. The SMART Tile project described is rooted in the performative displacement of materials to give architecture new climatic and experiential prospects. The building façade is thus viewed as a self-organizing operable filter that responds to differences between interior and exterior environments. Most kinetic building envelopes are predominately mechanical, relying on an interconnected series of sensors, motors, and computational feedback loops to adjust interior conditions in response to climatic variations. Less studied are adaptive building technologies that reduce mechanical complexity by employing the programmable behavior of 'smart,' 'responsive,' or 'dynamic' materials. Among smart materials being developed, shape memory polymers (SMPs) have particularly useful properties for building technology. SMPs are programmable, exhibit variable stiffness, undergo extremely large deformation without fatigue damage, and require minimal actuation force to change shape. In building technology applications SMPs can morph to a number of preprogrammed shapes, effectively using smart material properties (i.e. material computation) to reduce system complexity by lowering reliance on external sensors, wiring, electronics, and digital computation.

The goal of this proof-of-concept project is to develop smart material tiles for building envelopes that predictably change shape in response to heat and applied air pressure for self-shading facade applications. More specifically, the technology proposed is to be applied to an adaptive building skin that can change its geometric configuration to alternatively shade or absorb solar energy to control thermal transmission at the building envelope. A future speculative goal for the team is step beyond self-shading strategies and design soft SMP actuators that optimally normalize photovoltaic arrays toward the sun. The SMART Tile project was inspired by current research on dynamic airplane wing design for in-flight wing profile changes to increase maneuverability and fuel efficiency [2].

The benefits of a more responsive architecture are reduced energy consumption and the psychological effects of human awareness of environmental variation. Buildings have long been designed to provide shelter and in the best cases, reinforce one's connection to a place. Relatively recently, the quest for comfort via centralized heating, air conditioning, and the practice of hermetically sealing building envelopes, has physically and emotively separated inhabitants from the environment. In addition to constructing buildings that operate with less power, designing with dynamic or smart materials has the prospect to address the waning physical connection of building to place, and of building inhabitants psychological connection to nature.

2. Dynamic material properties

2.1 Shape memory effect

The ability of a material to be deformed and then recover to its previous shape when subject to particular stimuli is known as the shape memory effect. First observed in alloys in the 1930's this effect may be induced by light, heat, electricity, magnetism, or vibration. The shape memory effect was coined from the study of alloys where the most shape memory research has been conducted. Shape memory polymers differ from their alloy counterparts as they have lower density, exert less force upon recovery, and are able to undergo significantly higher strains. Until recently the effect was considered an exotic characteristic of a small class of materials, yet research is emerging demonstrating that shape memory effect is a relatively generic property of many materials [3]. Shape memory research is rapidly expanding as most synthetic and natural polymeric materials, including human hair [4] and even wood [5] exhibit some shape memory effect.

2.1.1 Temperature activated SMPs

Temperature activated polyurethane polymers have a significant and reversible change in elastic modulus across its glass transition temperature (Tg), the temperature at which the material is able to be easily deformed and which it can recover to a preprogramed shape. The SMP used in this study is a thermally triggered polyurethane and holds a single permanent shape. Similar to shape memory alloys, the polymer works "one way," and requires a bias force to deform the material to a deformed position. Once the glass temperature is reached, the polymer transitions to its 'remembered' shape. During this transition, the material softens and exerts little force. Once cooled, the material significantly increases in stiffness and will permanently hold this shape unless heated. If heated to its Tg, strain is released and the material will recover to its programmed form. This process can be repeated without material fatigue. For SMP's, the glass transition temperature may be modified enabling the material to respond to a wide range of temperature variation.

Thermally activated shape memory polymers have been chosen for this proof-of-concept study as they are by far the most studied and available SMP variant and are therefore better understood mechanically than other smart polymers. It is noted that thermally activated polymers are not the ideal material for the application to be translated to the practical application of a building facade. In particular, the energy cost of the activation of thermally activated SMP is inferior to other SMP types (e.g., light activation has been shown to require an order of magnitude less energy than thermal activated polymer [6]. However, all major contributions of the proposed work are expected to be applicable to other less-established SMP types (e.g., light or electrically responsive), which are predicted to be more feasible in practice, and will be a subject for future work. Another prospect of overcoming the relatively high energy requirements of thermally activated SMPs is to target the Tg to specific latitudes and building types, and use energy from the sun to attain the Tg.

2.2 Self-shading articulated surfaces

2.2.1 Cacti and buildings

Seemingly alien, cacti differ significantly from other flora. Upon closer inspection, cacti are highly adapted to their environment and their acclimatization to extreme environments is the source of their strange beauty. In response to high solar insolation, cacti transformed their leaves to spines, and transferred the site of photosynthesis to their trunk in a remarkable effort to balance abundant sunlight with water loss through transpiration. As they shed their leaves, cacti evolved self-shading strategies along their trunk. These self-shading undulating surfaces (Fig. 1) were studied to establish a baseline wrinkling pattern for the SMART Tile. Also shown in this figure, is a previous study of a static tile drawn from cacti wrinkling patterns [7].

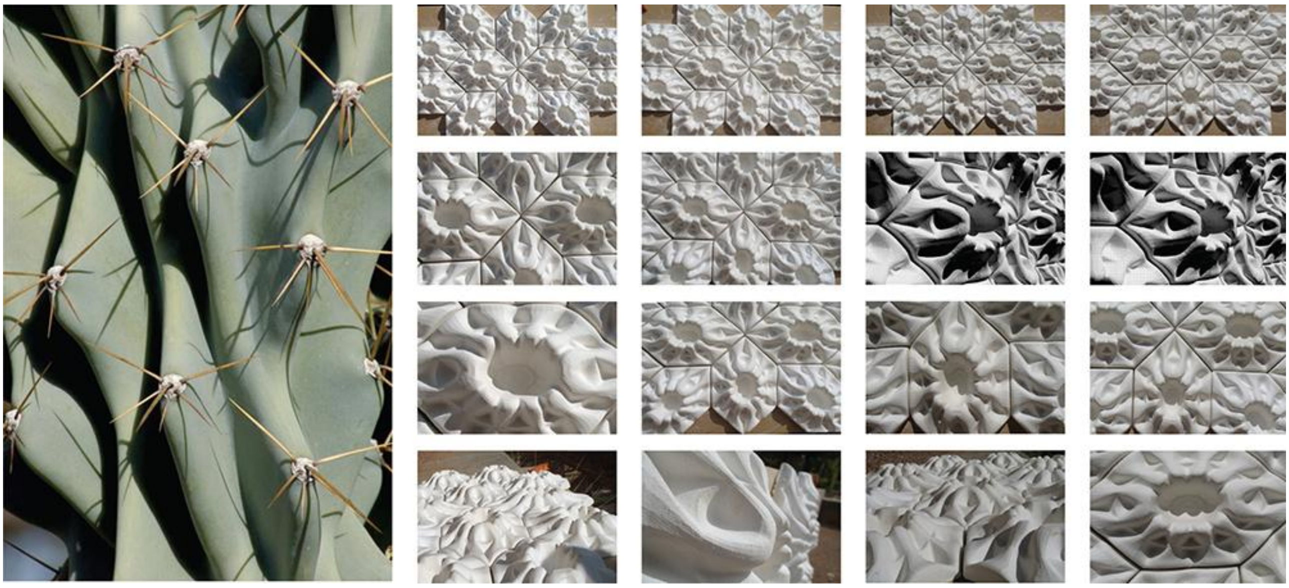

Figure 1: Self-shading cactus skin with previous static tiles. The craft of building has from borrowed from natural sources.

3. Prototyping

3.1 Polymer forming

3.1.1 Casting and printing

The two methods of making the tiles are casting a two-part polyurethane polymer resin system and 3-d printing of polyurethane filament. Two-part resins and SMP filament are currently available from SMP Technologies, a spin-off of Mitsubishi Heavy Industry. The two-part system has a Tg of 25C and the filament system has a Tg of 55C. Memory is thermoset into the SMP through by both casting and printing. For example, if cast, this shape is the memory state. If printed, the printed shape is the memory state that the material will recover to.

3.1.2 Cast composite tiles

In order to gain control over the tile's deformed state a second stiffer material was cast with the SMP (Fig. 2). The stiffer material is ABS plastic printed with a 3-d printer. The cast SMP is isotropic while the printed ABS can vary in directional stiffness depending on the patterning of the print. The resultant tile has variable stiffness as the SMP has a lower elastic modulus (especially when heated above the Tg) than the printed ABS.

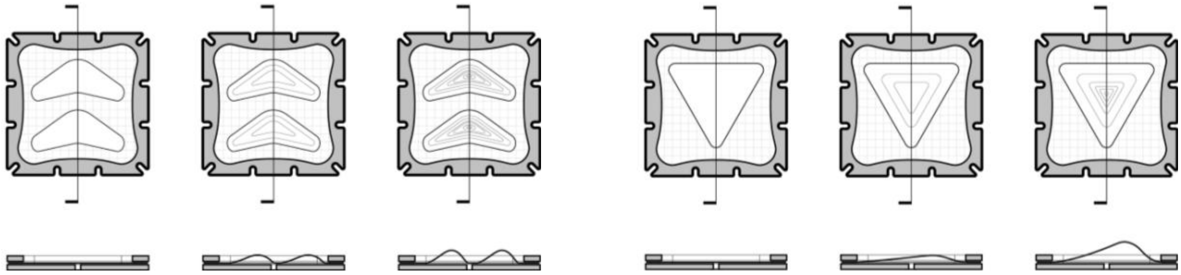

Fig. 2 Variable stiffness composite tiles made from shape memory polymer and ABS plastic showing sequential actuation. The lower series of drawings indicate the deformed tile shape.

3.1.3 Varible thickness tiles

A second series of prototypes were made via 3-d printing with SMP filament. Tiles were constructed of uniform thickness and variable thickness. In the variable thickness tiles, thicker regions transferring heat at different rates than thinner regions, forming a variable stiffness sample composed of a single material. Figure 3 is an initial attempt to gain control of the deformed shape of a variable thickness tile that was subject to consistent low air pressure and even heating. The tile exhibits greater deformation in areas of least material thickness.

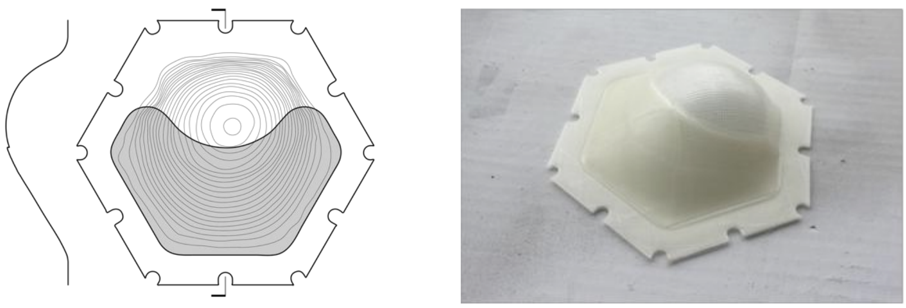

Figure 3 Variable thickness tile. Shaded region 1/16" thicker than base thickness. Topo lines show amount of deformation. A variable thickness printed SMP tile is shown to the right.

3.2 Workflow

The workflow is to cast or print SMP tiles, fit the tiles to the test jig, and then deform the tile with applied heat and pressure. Removal of heat causes the tile SMP to cool, pressure is then released, and the tile retains the deformed shape. Photogrammetry is then used to digitize the deformed shape for measurement and sent to the morphology team to validate the computational design techniques. The mesh is also used for input to solar analysis software to determine shading potential of the tile over time. Preliminary solar analysis was performed in Diva for Phoenix, AZ, noon, summer solstice, and facing south (Figure 4).

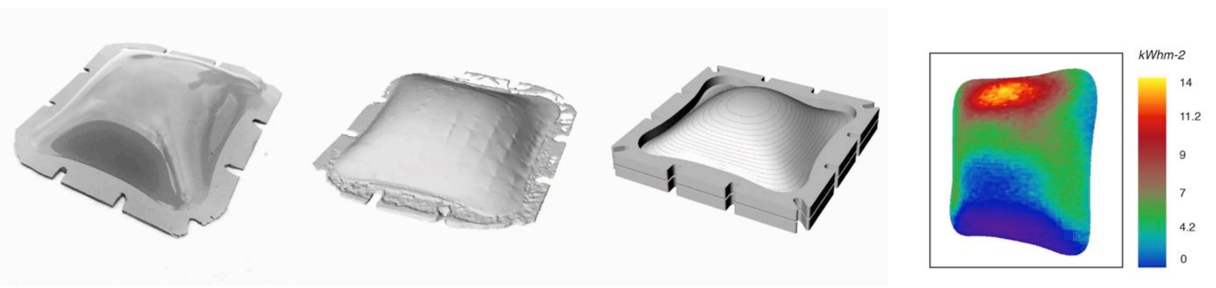

Figure 4 SMP tile after subject to uniform heating and uniform pressure, photogrammetry surface, digital reconstruction. Diva solar insolation analysis (Phoenix, AZ, south-facing, summer solstice, 12-2 pm) of digital reconstruction.

3.2.1 Test jig and sample testing

A test jig was designed to clamp the SMP tile in place and have an entry point for pneumatic actuation. Figure 5 shows an assembly diagram of a test jig with a composite sample in place. The jig is airtight and pressurized to .3 kpa (.05 psi) then the SMP sample is heated, via a heat gun, to just above its Tg. At this point the material becomes highly deformable, requiring little air pressure for deformation. Once in the deformed state, the heat is removed and when cooled below the Tg, the shape is held. If the deformed tile is heated above the Tg, it returns to its initial (cast) shape. An area for future research is to target how the material is heated, and then with air pressure constant, a variety of morphologies can be attained from a single tile. Testing of composite ABS/SMP samples shows the expected deformed shape (Figure 6).

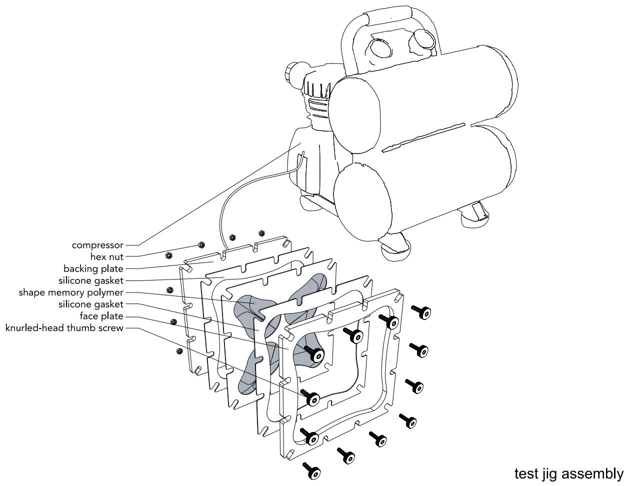

Figure 5: Test jig assembly with composite hard plastic / shape memory polymer sample.

Figure 6: Images of deformed SMP in the test jig. Air pressure is let in through the back of the jig. The first image has a cast uniform thickness SMP sheet, the second is a composite tile composed of a printed ABS mask (white) cast within a AMP sheet. Drawing showing multiple tile assembly.

3.3 SMART Tile Panel System

3.3.1 Façade system

The tiles are proposed to form a façade system (Figure 7,9) that applies the shape memory effect of the polymer to reduce building envelope thermal transfer in hot/arid climates. The system is dynamic and designed to continually adjust to local solar incidence with a single means of actuation (consistent low air pressure) and perhaps a single tile. The variation in shape is related to how the tile absorbs heat. For instance in Figure 8, tile deformation is directly related to heat transfer on the tile surface. The same tile could take numerous forms throughout the day and continually adjust itself to solar angles.

One of the principles guiding this study is that increased surface area can provide shade and also aid in the dissipation of heat on a building façade. Another is that further exploration will allow the tile to potentially collect light, and if desirable, transfer heat to the building interior during the winter months.

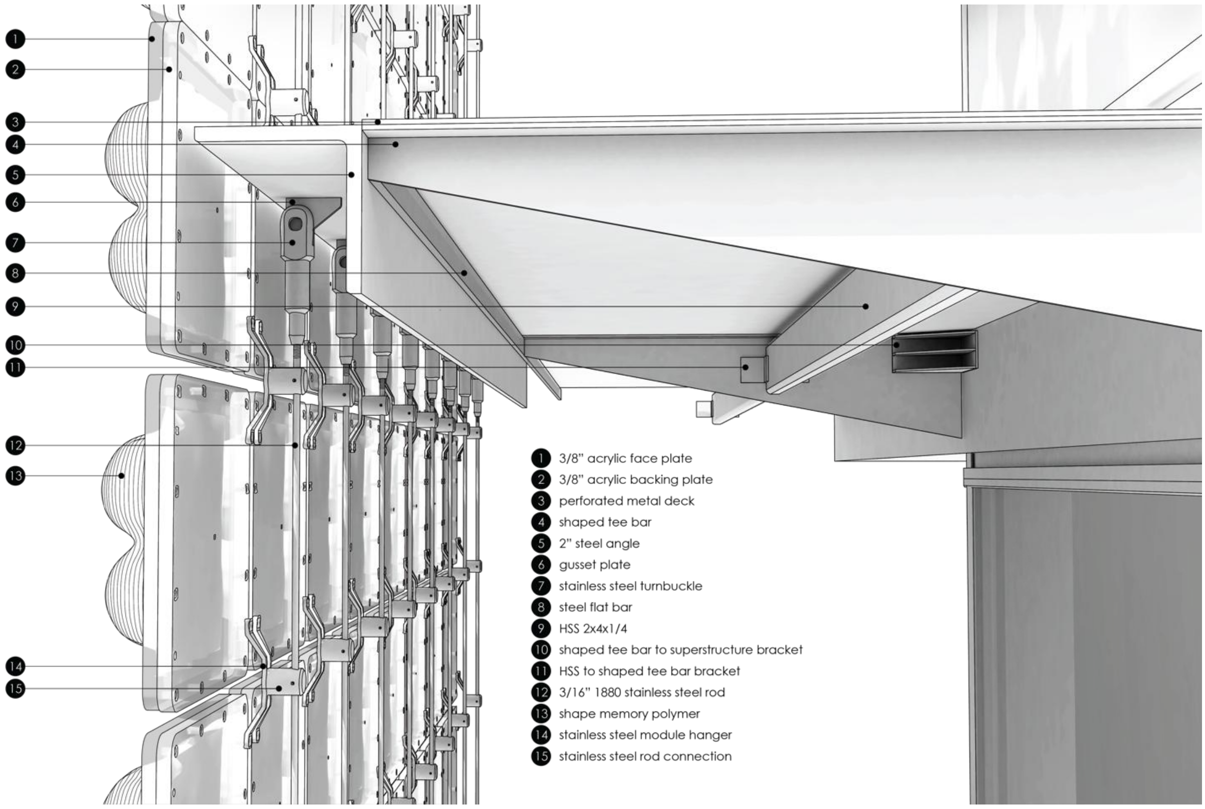

Figure 7: Rainscreen assembly composed of shape memory polymer tiles.

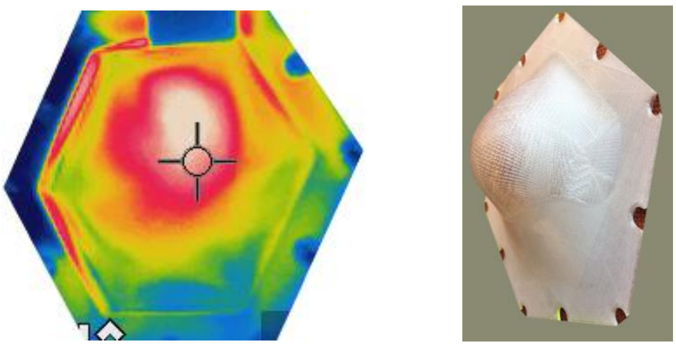

Figure 8: Thermal image (elevation view) showing the relationship between heat distribution and deformed shape (oblique view) for a printed SMP tile.

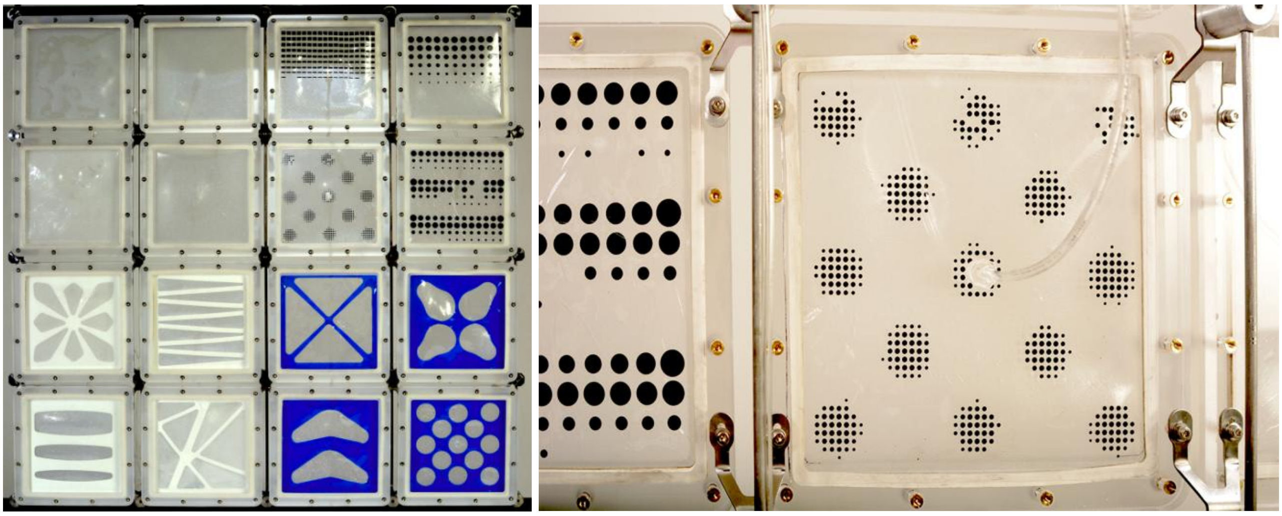

Figure 9: 16 tile test showing explorations in controlling deformation (lower two rows are composite tiles, upper right quadrant show experiments with fritting to localize thermal transfer, upper left quadrant shows variable thickness tiles. The figure to the right shows fritting pattern with air inlet for tile actuation.

3.3.2 Issues and considerations

The team is gaining competency in casting and printing SMPs, and experience in deforming the material with heat and air pressure. Many questions have arisen during this study regarding the relationships between solar insolation, material thickness, and thermal transfer in regards to control of tile deformation. A significant concern is designing methods of thermal control to allow the tile to recover to its initial state. Other considerations include energy harvesting and embedding photovoltaic cells into the polymer that can be continually normalized to solar angles. The team also plans to consider adding attributes to the tile, and by extension exterior building surfaces, that include wind pressure distribution and water channelling.

4. Conclusions

Responsive materials are being extensively researched in the sciences and becoming more commonly and economically available to the architect and designer. As responsive materials are better understood and applied, nuanced relationships will emerge between the built and natural environments. This project is part of an ongoing attempt to produce an adaptive building surface that is attuned to climatic change through the properties of smart materials. The SMART Tile façade is a non-linear self-regulating system that responds to multiple solar insolation states rather than a single optimized state. As temperature increases, so does the articulated surface of the façade, dynamically providing shading in balance with light and temperature. By enabling a building façade to dynamically vary its surface topography, we may both lower energy consumption and contribute to the emergent field of responsive building technologies driven primarily by the behaviour of smart materials. This area of architectural inquiry draws from the dynamic, soft, and pliant adaptive approaches found in nature. In this sense, the proposed building façade is an instrument that helps to adjust our attitude towards compliance and exchange between the built and natural environment.

5. Acknowledgements

Thanks to Alyssa Parr and Jesse Chin for solar analysis, Craig Kimball for knowledge of three-dimensional printing, Jay Miley for assistance with mechatronics, and Prof. Kelle Brooks for design insight.

This project is supported by the National Science Foundation, Structural and Architectural Engineering and Materials, Award number 1536721 and the American Institute of Architects Upjohn Research Initiative Award.

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